Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 6 (2020) 1636–1640
www.elsevier.com/locate/egyr

The 6th International Conference on Power and Energy Systems Engineering, CPESE 2019,20–23 September 2019, Okinawa, Japan

An estimation model based on solar geometry parameters for solar power production

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Received 12 October 2019; received in revised form 21 March 2020; accepted 22 March 2020

Abstract

Renewable energy sources are can play an important role both in fulfilling the increasing demands for energy and in reduction of the emissions of the greenhouse gases and other air pollutants. For these reasons their energy yield increases dynamically. Renewable energy sources are available in different ratios in different regions of the continents. Every regions has its own features what result in different utilisation methods. This paper presents a solar energy potential estimating model what can be used at any locations over the Earth. Examinations were carried out on a remote controlled system composed of 64 solar panels in the Renewable Energy Park Research Center in Debrecen, Hungary. Results revealed that the agreement between the model and the values in our database is over 90% thus using the model the production of the solar panel systems could be predicted taking into account specific local conditions as well.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering, CPESE 2019.

Keywords: PV systems; Solar energy; Estimating model

1. Introduction

One of the most important problems affecting every member of the society in the 21st century is climate change and its consequences. Apart from biodiversity decrease and the decrease of the number of species together with climate zone shifts, satisfying an increasing energy demand has to be solved also. Although satisfying this demand is not possible in 100% using energy from environmental friendly and CO_2 free technologies but these could contribute to the significant reduction of harmful material emission. The share of renewable energy resources was doubled in the European Union between 2004 and 2016 – [1] – thanks to, on the one hand, an energy policy supporting similar efforts and, on the other hand, technological development and the fall of the price of such technology. Solar energy has been one of the most dynamically developing branches in recent years considering renewable energy resources.

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https://doi.org/10.1016/j.egyr.2020.03.033

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering, CPESE 2019.

Nomenclature

D	is the so called Julian date, the ordinal number of calendar days in a year
η	Hour angle
H	Studied hour
α	Solar altitude
φ	Geographical latitude
δ	Declination angle
β_s	is solar azimuth
β_ι	Aspect angle
χ	Slope angle
S_c	Solar constant
S_{out}	Amount of radiation arriving to the outer surface of the atmosphere
τ	Thickness of the atmosphere and its optical permeability
P_h	Air pressure measured at any height Introduction
P_0	Air pressure measured at sea level
S_{dif}	Diffuse radiation
S_{in}	Global radiation

There are two distinct methods of solar energy utilisation: sanitary hot water production and electricity production. In 2017 regarding photo voltaic (PV) capacity the total power of the top three countries was 345 GW, IEA [2]. More than one third of this power was given by China (131 GW), U.S. (51 GW) and Japan (49 GW). The rate of investment in the given years is also an indicator of development. The above mentioned three countries installed 53, 10.6 and 9.1 GW capacity respectively in 2017. These values are mostly provided by solar panel parks covering tens of hectares but also small, household sized systems producing for the central network also occur in high numbers nowadays. The size of these systems is typically smaller than 20 kW in capacity and similarly to major solar panel parks these are installed on the earth's surface as well (with a tilt angle corresponding to local conditions). Systems with a few kW capacity are installed typically on roofs. Covering available roof surfaces with solar panels results in a significant reduction of costs depending on the size of the available area and if production exceeds consumption in the household solar energy could yield a profit. A method for optimising the location of such small and medium sized household systems taking consumption also into account is presented in this paper. Consumption determines primarily the size of the system. The primary aim of the study is to prepare an energy estimating model based on geometric principles that could be applied anywhere on Earth.

2. Methods

The amount of radiation energy reaching the earth's surface depends on a number of variables like the place of Sun and Earth relative to each other, the angle of incidence of solar rays, atmospheric transparency and height above sea level. The basis of the estimation model is to calculate the total annual radiation relative the studied point by adding up the amount of radiation in every hour of the year. The value of estimation can be calculated by using the following geometric relationships.

The angle of declination (δ) is the angular distance of the sun from the celestial equator. The value for this varies between $-23°$ and $+23°$ daily. It can be calculated using the equation below, Kumar et al. [3]; Németh [4]:

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{\mathrm{D} + 284}{365.25}\right) \tag{1}$$

where D – is the so called Julian date, the ordinal number of calendar days in a year (1st January is the 1st day according to the Julian date while 31st December is the 365th day or 366th day in a leap year).

The hour angle (η) describes the seeming movement of the Sun around Earth. Its value shows the seeming place of the Sun towards east or west compared to the local meridian. Its value is negative in the morning and positive in the afternoon and 0 when the Sun is right on the meridian.

$$\eta = 15 \cdot (\mathrm{H} - 12) \tag{2}$$

where H – is the studied hour.

The height of the Sun above the horizon is given by the solar altitude (α). Solar altitude changes continuously, its value is 0 at sunrise and sunset while its maximum is reached at culminate. Culmination height is also different in every season, Gates [5].

$$\sin\alpha = \sin\varphi \cdot \sin\delta \cdot \cos\varphi \cdot \cos\delta \cdot \cos\eta \tag{3}$$

where φ – is geographical latitude, δ – is declination angle, and η – is hour angle.

The azimuth angle of the Sun (β_s) is the angle between solar rays and the N–S direction of the earth. It is calculated based on the following equation for which we have to know geographical latitude (φ), declination angle (δ), hour angle (η) and solar altitude (α), Page [6]:

$$\cos\beta_\mathrm{s} = \frac{(\sin\varphi \cdot \sin\alpha - \sin\delta)}{\cos\varphi \cdot \cos\alpha} \tag{4}$$

The angle of incidence of solar rays can be calculated on the basis of the equation below:

$$\cos\iota = \cos\alpha \cdot \sin\chi \cdot \cos(\beta_\mathrm{s} - \beta_\iota) + \sin\alpha \cdot \cos\chi \tag{5}$$

where α – is solar altitude, β_s – is solar azimuth, β_ι – is aspect angle, χ – is slope angle.

A key part of the estimation model is global radiation calculation on the basis of solar geometric parameters determined above and of physical relationships described in an empirical way. As a first step, the amount of radiation arriving to the outer surface of the atmosphere (S_{out}) has to be determined. The value of this depends on the solar constant and the Sun–Earth distance. Several studies determined different values for the solar constant (S_c): Monteith and Unsworth [7] gave a value of 1373 W m^{-2} while 1353 W m^{-2} appears in the NASA report, Jansen [8]. In this paper the value of 1367 W m^{-2} accepted by the World Radiation Centre is used, Duffie and Beckman [9]. Based on the work of van Dam [10], solar radiation energy (S_{out}) arriving to the outer surface of the atmosphere can be calculated on the basis of the following equation:

$$\mathrm{S_{nor}} = \mathrm{S_c} \cdot \left(1 + 0.034 \cdot \cos\left(360 \cdot \frac{\mathrm{D}}{365}\right)\right) \tag{6}$$

Solar rays arriving to the outer surface of the atmosphere have to penetrate the atmosphere in the course of which losses occur. The amount of energy loss depends on the thickness of the atmosphere and its optical permeability (τ). Solar radiation energy reaching the earth's surface can be calculated using the following equation according to van Dam [10]:

$$\mathrm{S_{nor}} = \mathrm{S_{out}} \cdot \tau^{\mathrm{M_h}} \tag{7}$$

where:

$$\mathrm{M_h} = \mathrm{M_0} \cdot \frac{\mathrm{P_h}}{\mathrm{P_0}} \tag{8}$$

where:

$$\mathrm{M_0} = \sqrt{1229 + (614 \cdot \sin\alpha)^2} - 614 \cdot \sin\alpha \tag{9}$$

and

$$\frac{\mathrm{P_h}}{\mathrm{P_0}} = \left(\frac{288 - 0.0065 \cdot \mathrm{h}}{288}\right)^{5.256} \tag{10}$$

Literature calls P_h/P_0 pressure correction where P_h is air pressure measured at any height while P_0 is air pressure measured at sea level.

Direct radiation can be described with the following relationship based on radiation arriving to the surface and the angle of incidence of solar rays:

$$\mathrm{S_{dir}} = \mathrm{S_{nor}} \cdot \cos\iota \tag{11}$$

Direct radiation is only one component of global radiation. The other component is radiation scattered by particles in the atmosphere, in other words diffuse radiation. Diffuse radiation was determined by van Dam [10] with the following equation:

$$S_{dif} = S_{out} \cdot \left(0.271 - 0.294 \cdot \tau^{M_h}\right) \cdot \sin\alpha \tag{12}$$

Global radiation (S_{in}), i.e. the total amount of incoming radiation is the sum of the direct and diffuse radiation:

$$S_{in} = S_{dir} + S_{dif} \tag{13}$$

In the case of solar panel systems the system loss of 14% was used in the calculations that occurs in the PVGIS system developed by the European Union. This means that in the case of solar panel systems this 14% has to be deducted from the obtained energy production values to know the final production values at a given area with a certain tilt angle and aspect.

3. Results

The model composed on the basis of the presented method was tested in several areas and the results were compared to the data of PV GIS (PV GIS web) online solar energy calculation application. After giving the data of location (geographical coordinates) and aspect the tilt angle of the panel can be given as well. The approximate production rates of the solar panel are presented graphically in a monthly break down by the webpage. The database available at the webpage covers most dry land therefore the webpage and its results are taken for comparison. The comparison revealed that the agreement between our model and the PV GIS is 90% globally (in the area covered by the PV GIS database). Difference from this can be found in two climate zones: the tropical and the subtropical zones. Both zones showed an agreement of 80%–85%. Inaccuracy in the tropical zone is the result of an overestimation in our model due to the continuous formation of cumulus clouds. The opposite occurs in the subtropical zone where the model gives underestimations due to the lack of clouds. Our model shows an agreement of higher than 90% in Hungary in the temperate zone based on a comparison with the production data of more than 50 operating solar panel systems.

4. Discussion

The model shows an accuracy of 90% in relation to the incoming solar radiation on the basis of the available data. Differences from this value can be found only in the tropical and subtropical zones with 80%–85% of agreement. It can probably be explained by that our model does not take into account the temporal and spatial differences of cloudiness. However, clouds have a remarkable effect on actual values of global irradiance. For instance cumulus type clouds frequent in the inner tropical areas can absorb more than 80% of incoming shortwave radiance. For this reason our model gives an over estimation for the inner tropical areas where strong cloud cover is frequent and gives an underestimation for the subtropical areas because of the lack of clouds in those regions (Table 1).

Considering that the agreement between the model and the online database is around 90% and that the majority of the continents are covered by the test areas it can be stated that similar results could be expected in areas outside the coverage of the webpage as well. When the results of the model are compared to real production data in the temperate zone (in Hungary) the agreement is higher than 90%. Using the model the annual amount of global radiation can be calculated to any place on Earth with different orientations and tilt angle that significantly helps the design of small and medium sized solar panel systems. Using the PV Calculator production forecast can be given for up to one year at any site. Even shorter time periods can be calculated as well (even 1 day) regarding different sizes, tilt angles and aspects for the solar panel system. Knowing the energy consumption the production of the solar panel system can be optimised and a system with optimal location and size can be designed that covers the energy consumption as completely as possible. In this way costs can be minimised while income can be maximised and return rates can also be reduced to a minimum. Since there could be a difference of even 40% between the production rates of the 64 systems controlled by the Renewable Energy Park Research Center depending on location and system size, the development of an optimising PV Calculator would be necessary.

Table 1. The differences between estimated and measured values.

Latitude	Longitude	PV calculator	PV GIS	%
61.36 N	22.46 E	633.01	691.88	109.3
59.64 N	63.24 E	666.13	763.46	114.61
55.85 N	114.32 W	757.68	857.67	113.20
38.47 N	96.01 W	1112.08	1270.37	114.23
38.50 N	76.85 W	1099.19	1199.23	109.10
48.44 N	4.01 E	893.9	957.39	107.10
47.52 N	21.49 E	912.42	1000.47	109.65
20.84 N	4.32 E	1412.89	1767.23	125.08
20.87 N	26.83 E	1423.33	1922.72	135.09
28.53 N	41.30 E	1317.7	1677.55	127.31
15.87 N	49.31 E	1499.3	1818.22	121.27
25.54 S	18.69 E	1395.64	1757.77	125.95
5.32 S	19.38 E	1566.76	1406.66	89.78
4.45 N	11.18 E	1555.05	1486.28	95.58
0.09 S	113.97 E	1557.55	1257.07	80.71
3.21 S	71.85 W	1548.03	1275.38	82.39
3.79 S	45.41 W	1542.34	1503.66	97.49
Average				109.28

5. Conclusions

It has been proved that our model provides a good estimation for the amount of solar power available in different regions in the mid and high latitude zones of the earth as a function of solar geometry parameters.

Our model gives less accurate estimations for the low latitudes since it cannot handle the effects of cloudiness yet.

A future aim of the research is to improve the accuracy of the estimations for tropical and subtropical zones to at least 90% of agreement similarly to the rest of the areas with integrating further influencing parameters into the model. The next step in the development of our model will be to build in the effects of cloudiness on actual amount of global irradiance in any given point on Earth at any given time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The publication is supported by the EFOP-3.6.1-16-2016-00022 project. The project is co-financed by the European Union and the European Social Fund.

References

[1] Eurostat. Share of renewables is energy consumption in the EU reached 17% in 2016. 2018.
[2] International Energy Agency. Snapshot of global photovoltaic markets. Report IEA PVPS T1-336:2018, 2018.
[3] Kumar Lalit, Skidmore Andrew K, Edmund Knowles. Modelling topographic variation in solar radiation in a GIS environment. Int J Geogr Syst 1997;11(5):475–97.
[4] Németh Ákos. Modelling of global radiation using evelation model (in hungarian). In: HUDEM 2004. 2004.
[5] Gates David M. Biophysical ecology. Springer-Verlag; 1980.
[6] Page JK, editor. Prediction of solar radiation on inclined solar energy R & D in the european community, series F. Solar Radiatin Data, vol. 3, D Reidel Publishing Co; 1986.
[7] Monteith John L, Unsworth Mike H. Crop micrometeorology (ii) interpretation of measurements. In: Principles of environmental physics by monteith and unsworth. 2nd ed.. Edward Arnold; 1990.
[8] Jansen Ted J. Solar engineering technology. Prenctice Hall; 1985.
[9] Duffie John A, Beckman William A. Solar engineering of thermal process. John Wiley; 1991.
[10] van Dam Oscar. Forest filled with gaps. Effects of gap size on water and nutrient cycling in tropical rain forest. (a studie in Guyana). Enschede: PrintPartners Ipskamp B.V.; 2001.